

Comparison of stand structure and growth between artificial and natural forests of *Pinus sylvestris* var. *mongolica* on sandy land

ZHU Jiao-jun^{1,2}, FAN Zhi-ping¹, ZENG De-hui¹, JIANG Feng-qi¹, MATSUZAKI Takeshi²

¹Institute of Applied Ecology, the Chinese Academy of Sciences, 110016 Shenyang, P. R. China

²Faculty of Agriculture, Niigata University, 950-2181 Niigata, Japan

Abstract: Mongolian pine (*Pinus sylvestris* Linnaeus var. *mongolica* Litvinov) as a valuable conifer tree species has been broadly introduced to the sandy land areas in "Three North" regions (North, northwest and northeast of China), but many problems occurred in the earliest Mongolian pine plantations in Zhanggutai, Zhangwu County, Liaoning Province (ZZL). In order to clarify the reason, comprehensive investigations were carried out on differences in structure characteristics, growth processes and ecological factors between artificial stands (the first plantation established in ZZL in 1950s) and natural stands (the origin forests of the tree species in Honghuaerji, Inner Mongolia) on sandy land. The results showed that variation of diameter-class distributions in artificial stands and natural stands could be described by Weibull and Normal distribution models, respectively. Chapman-Richards growth model was employed to reconstruct the growth process of Mongolian pine based on the data from field investigation and stem analysis. The ages of maximum of relative growth rate and average growth rate of DBH, height, and volume of planted trees were 11, 22 years, 8, 15 years and 35, 59 years earlier than those of natural stand trees, respectively. In respect of the incremental acceleration of volume, the artificial and natural stands reached their maximum values at 14 years and 33 years respectively. The quantitative maturity ages of artificial stands and natural stands were 43 years and 102 years respectively. It was concluded that the life span of the Mongolian pine trees in natural stands was about 60 years longer than those in artificial stands. The differences mentioned above between artificial and natural Mongolian pine forests on sandy land were partially attributed to the drastic variations of ecological conditions such as latitude, temperature, precipitation, evaporation and height above sea level. Human beings' disturbances and higher density in plantation forest may be ascribed as additional reasons. Those results may be potentially useful for the management and afforestation of Mongolian pine plantations on sandy land in arid and semi-arid areas.

Keywords: *Pinus sylvestris* var. *mongolica*; Mongolian pine; Sandy land; Comparison; Growth model

CLC number: S791.253

Document code: A

Article ID: 1007-662X(2003)02-0103-09

Introduction

There is extensive sandy land in China, and the total area of desertification in sandy soil has reached 1.53×10^9 hm², in which most of the area distributes in "Three North" regions (Northwest, North and Northeast of China) (Jiang *et al.* 1993a; Zhu *et al.* 1994). The "Three North" regions are the arid and semi-arid areas, which are characterized by low and unreliable rainfalls, extreme temperature, strong wind, high evaporation and poor soils. Planting trees as a main countermeasure to construct protection system against sand movement and improve environment quality has a long tradition in the worldwide (Jiao 1989; Jiang *et al.* 1993b). In China, the "Three North" Protective Forest System Project, which covers more than 42% area of China,

including 13 provinces or autonomous regions, was started in 1978, and the total area of the protective forests has attained to 1.533×10^7 hm² in the first two periods (the first period was from 1978 to 1986, the second period was from 1987 to 1996). The project has increased the forest coverage of "Three North" regions from 5.5% to 7.6% in the past twenty years. The protective forest system has brought totally more than 3.30×10^7 hm² of farmland, sandy land and pasture under protection.

As a main tree species on sandy land, the Mongolian pine (*Pinus sylvestris* Linnaeus var. *mongolica* Litvinov) is a geographical variety species of Scotch pine (*Pinus sylvestris* Linnaeus) (Jiao 1989). It naturally distributes in Daxing'an Mountain and Hulunbeier sandy plain of China, and parts of Russian and Mongol (N46°30'-53°59', E118°00'-130°08'). Its vertical distribution is from 600 m to 2000 m above sea level (ASL) (Wang *et al.* 1996). The natural distribution of Mongolian pine on sandy land includes Honghuaerji (the largest area), Haila'er, Wangong, Cuogang, He'erhongde, Hunhe and Ha'erhahe areas in Inner Mongolian Autonomous Region, and formed a natural forest belt about 200 km long and 14 to 20 km wide at its mean in the fixed sandy dunes of above-mentioned areas.

Foundation item: The research was supported by innovation research project of Chinese Academy of Sciences (KZCX3-SW-418), and by Nature Science Foundation of Liaoning Province (20021006).

Biography: ZHU Jiao-jun (1965-), male, PhD advisor, Professor of Institute of Applied Ecology, the Chinese Academy of Sciences, China; Scholar researcher of Faculty of Agriculture, Niigata University, Japan.

Email: jiaojunzhu@iae.ac.cn

Received date: 2003-03-05

Responsible editor: Song Funan

On account of the cold-resistance (-40 to -50 °C), drought resistance and broad adaptation (Zeng *et al.* 1996a), the Mongolian pine has been broadly introduced from the origin of Hulunbeier sandy land to many parts of China, especially in "Three North" Protective Forest System Project. The principal aim of planting Mongolian pine plantation is to fix the sandy land, reduce soil desertification and supply timber (Jiang *et al.* 1997). The earliest Mongolian pine plantation (1.07×10^4 hm²) was introduced and established in 1955 in Zhanggutai, Zhangwu County, located at the south of Ke'erqin sandy land, the northwest of Liaoning Province of China, which was surrounded by mobile and semi-mobile sandy dunes.

With the success of introduction on sandy land in 1950s, Mongolian pine plantations have been developed in a large scale of sandy land in "Three North" of China. Up to 1995, the area of Mongolian pine artificial forest had reached 4.0×10^6 hm², besides, during the third period (from 1997 to 2006) of "Three North" Protective Forest System Project 5.0×10^6 hm² of Mongolian pine plantations will be established. Most of the Mongolian pine plantations are sand-fixation forests. Although it had been successful in establishing Mongolian pine stands by planting seedlings on sandy land, degenerating phenomena such as top withered, lower growth and dead stems have occurred in the earliest Mongolian pine plantations since later of 1980s, however, the natural stands showed a very healthy situation at the same stage of plantations. Therefore, it is very important and significant to understand the reasons why the degeneration of artificial Mongolian pine forests occurred.

The objective of this study is to compare the ecological variations, stand structure and growth processes of the earliest Mongolian pine plantation introduced in 1955 in Ke'erqin sandy land, Zhanggutai of Liaoning Province (PKZL), with the natural origin Mongolian pine forests in Hulunbeier sandy land, Honghua'erji of Inner Mongolian Autonomous Region (NHHI). It is expected that the comparison could reveal significant differences between the two origins of Mongolian pine forests, and further give some explanations on the plantation decline. Such comparison results would partially provide evidences for afforestation and management of large-scale artificial Mongolian pine forests on sandy land.

Methods and materials

Data collection

After a thorough reconnaissance of distribution of pure Mongolian pine forests, comprehensive investigations including tree and stand characteristics, site, ecological conditions etc. were conducted in NHHI region for natural Mongolian pine forests and in PKZL region for artificial Mongolian pine forests during 1992-1995. The two sites of NHHI and PKZL were selected because of their proximities of Mongolian pine forests in different origins; the site descriptions were listed as a comparison of ecological

descriptions were listed as a comparison of ecological factors in Table 3. As we stress our study on pure Mongolian pine forests, we set up 50 sample plots (11 plots of natural stands, 2 artificial stand plots in NHHI region, and 37 plots of artificial stands in PKZL region) to meet the following criteria: 1) Mongolian pine forest on sandy land, 2) Pure Mongolian pine forest, 3) Normal growth, 4) Visual homogeneity of environmental setting, especially, the stands on relative flat sandy land.

The area of sample plot was around 0.25 hm². The following contents were investigated for each sample plot:

Location.

Stand origin: Natural or artificial.

Site type: soil type, soil sample, and position of sandy dune.

Humus layer in forest stand.

Vegetation: species, cover degree.

Planting composition for plantation: tree species, arrangement.

Stand age: At least 5 standard trees were chosen for estimating the average age of natural forest using increment borer. The age of each plantation was determined by referencing the local forestry archives.

Stand density: Stems in the sample plot were counted completely for determining the current stand density.

Diameter at breast height (DBH): after measuring diameter all stems in the sample plot the stems of more than 4 cm in DBH were recorded.

Crown closure: Canopy closure was estimated using hemispherical photographic silhouettes.

Average height of stand: the heights of 10 trees with, the average diameter were measured for estimating the average tree height. Suppressed trees were not included in the height estimation.

Height under the branch: At least 10 stems were measured to determine the height under branch.

The characteristics of sample plot data were summarized in Table 1.

Ecological factors: Besides some factors mentioned above, meteorological information such as precipitation, evaporation, temperature and wind etc. were collected from the local meteorological stations. Additionally, the situation of disturbance was also recorded. Mechanical composition and nutrients of soil in two typical sample plots in NHHI and PKZL region were analyzed (Wang 1991) in the Lab.

Stem analysis: Stem analysis was made at older stands. The trees chosen for stem analysis were from the standard crown and diameter classes, and free of any obvious weather, insect or disease damage. Totally 23 stems were used for stem analysis, and the age of the trees ranged from 12 to 41 years for artificial stands, and from 28 to 214 years for natural stands, respectively. The height ranged from 5.2 to 21.5 m, and the diameter (DBH) ranged from 9.8 to 41.2 cm (Table 2). From the growth information of diameter and height based on the stem analysis, and changes in form, volume growth can be determined for a

given tree. Therefore, a major use of stem analysis is to reconstruct the tree development of diameter, height and

volume for fitting the growth-age equations (Dyer *et al.* 1987).

Table 1. Descriptive parameters of Mongolian pine sample plots used in the study: mean and range for stands characteristics

Number of sample plot in different type of sand land	Age /year	Density /stems · hm ⁻²	Mean diameter at 1.3 m /cm	Coefficient of variation for diameter	Crown width /m	Mean height /m
Total 50 sample plots: Aeolian sand (n=25), Alluvial sand (n=1), Soddy sand (n=24)	24.8 (11.0-66.5)*	1602.0 (300-3467)	13.6 (5.9-33.8)	0.232 (0.120-0.317)	2.96 (2.02-6.16)	7.89 (3.69-19.55)
37 sample plots for plantation in PKZL, Aeolian sand (n=23), Alluvial sand (n=1), Soddy sand (n=13)	20.9 (11.0-39.0)	1692.0 (364-3467)	11.5 (5.9-22.7)	0.225 (0.120-0.317)	2.88 (2.02-5.81)	6.49 (3.96-11.55)
2 sample plots for plantation in NHHI: Soddy sand (n=2)	26.0 (26.0-26.0)	1733.5 (1617-1850)	13.7 (13.4-13.9)	0.296 (0.294-0.297)	2.41 (2.40-2.41)	8.80 (8.20-9.40)
11 sample plots for natural stand in NHHI, Soddy sand (n=9), Aeolian sand (n=2)	37.91 (22.0-68.5)	1242.7 (300-3357)	20.6 (11.9-33.8)	0.242 (0.198-0.308)	3.32 (2.22-6.16)	12.42 (9.05-19.55)

Note: n: number of sample plots; * figures in brackets below the mean value is the range value.

PKZL: Ke'erqin sandy land, Zhanggutai of Liaoning Province; NHHI: Hulunbeier sandy land, Honghua'erji of Inner Mongolian Autonomous Region.

Table 2. Information of stem analysis used in the study, mean and range of the characteristics for stems

Group	Age (year)	Number of stems	Height /cm
Artificial stand in Ke'erqin sandy land,	<15	2	5.40 (5.20-5.60)**
	21-25	5	7.57 (5.96-8.70)
	31-35	2	10.24 (9.27-11.30)
	41-45	1	11.80
	31-35	1	13.72
	41-45	1	16.44
Natural stand in Hulunbeier sandy land,	46-55	1	17.02
	56-65	3	14.96 (13.35-15.78)
	66-75	5	16.05 (14.35-18.70)
	>200*	1	21.50
Artificial stand in Hulunbeier sandy land	31-35	1	13.7

Note: *: Single tree mixed in larch forest, the data was provided by Institute of Protective Forests, Heilongjiang Province, China (1993). **: The range is in brackets below the mean values.

Diameter distribution models

Diameter class distribution is essential to reflect the yield system of stand level, which provides growth estimates by diameter class (Bailey 1980), it can be estimated for use in such systems by taking a sample of trees in many stands, and then estimating the parameters of sufficiently flexible probability density function to approximate the sample diameter class distribution. Three uni-variate distribution functions (Normal, The Weibull, and Beta) were evaluated for their feasibilities to describe the diameter class distribution of Mongolian pine stands. Non-linear least square

methods were used to obtain the parameter estimates. The three distribution functions have probability density functions (pdf) of the following forms.

Normal distribution form:

$$f_N(x; \mu, \delta^2) = (1/\delta\sqrt{2\pi}) \exp[-(x-\mu)^2/2\delta^2] \quad (1)$$

where x is DBH (cm), μ and δ are parameters of normal distribution.

The three-parameter form of the Weibull function (Bailey *et al.* 1973; Bolstad *et al.* 1987; Shiver 1988):

$$F_W(x; a, b, c) = (c/b)[(x-a)/b]^{c-1} \exp(-c/b)^c \quad (2)$$

where $a \geq 0$, $b > 0$, $c > 0$, $x \geq a$; a is location parameter, b is scale parameter, c is shape parameter.

The location parameter a is used for estimating the smallest tree diameter, if a is given as 0, then equation (2) becomes:

$$F_W(x; b, c) = (c/b)(x/b)^{c-1} \exp(-c/b)^c \quad (3)$$

The two models (equations 2 and 3) are related by the transformation of $y=x+a$, thus, no loss in generality results by restricting our discussion to equation (3).

Beta distribution form:

$$F_B(x; v, w, u) = \int u^{v-1} (1-u)^{w-1} du \quad (4)$$

where v and w are specific values of the random Beta variate; $u=(x-x_{\min})/(x_{\max}-x_{\min})$, x_{\min} and x_{\max} are the minimum and maximum of DBH.

Stems whose diameters less than 0.4 times of the mean

diameter were excluded from the database used for estimation of diameter distribution functions. Diameter classes were constructed at regular intervals of 2 cm. The three distributions were evaluated by their relative accuracy in conforming to the empirical diameter distributions on the basis of residual patterns and Chi-square goodness-of-fit statistic $[(\text{observed-predicted})^2/\text{predicted}]$. The distribution was ranked on the basis of the Chi-square values computed from each sample plot and from different origins, while the total sum of Chi-square values was used as a general comparison of overall goodness-of-fit for Mongolian pine artificial and natural stands.

Growth process model

Growth of forest stands and trees has been studied from the beginning of forestry research since 1900, and quantitative analysis of forest growth has progressed rapidly both in extent and in degree of sophistication (Pienaar *et al.* 1973). Generally, the growth curves of DBH, tree height (H) and volume (V) are assigned to either Sigmoid forms or Reverse-J (Strub *et al.* 1975; Parker 1988; Vanday 1995). Thus, we should choose a growth model, which covers the "S" or Reversed-J shapes, plus relative growth rate variation with fitting both the Mongolian pine artificial and natural stands; and also should be sufficiently flexible to adequately fit the observed data and have easily interpretable parameters in order to compare the growth between the two-origin stands. The Chapman-Richards growth function has been applied since it was introduced to forest studies by Pienaar *et al.* in 1973, it has the characteristics mentioned above (Vanday 1995), and has been used to model growth almost to exclusion of all other growth models (Bailey 1980; Dyer *et al.* 1987; Bredenkamp 1988). Therefore, the three-parameter Chapman-Richards growth model was selected to simulate the growth of DBH, tree height and volume for both planted and natural Mongolian pine trees. The three-parameter form of the Chapman-Richards growth function is written as:

$$G_i(t) = G_{ias} \{1 - \exp[-\omega_i(t - t_0)]\}^{\lambda_i} \quad (5)$$

where $G_i(t)$ is total growth of forest stand, of which i represents diameter (d) (cm), height (h) (m) and volume (v) (m^3), respectively, and t is the age of forest stand (year), t_0 is the age at beginning (year), G_{ias} is asymptotic growth; ω_i is a coefficient related to growth rate (non-dimension), λ_i is a coefficient related to site index and graphic shape (non-dimension).

If $t_0 = 0$, then equation (5) becomes,

$$G_i(t) = G_{ias} [1 - \exp(-\omega_i t)]^{\lambda_i} \quad (6)$$

This simplified form has been found eminently suited to describe the growth of diameter, height and volume in simulation using stem analysis. Experience has shown that parameter estimates derived by no-linear least square are

statistically stable (Yang *et al.* 1987; Bredenkamp *et al.* 1988). Both stem analysis data and sample plot data were used to simulate the curves of diameter, height and volume.

Results and discussion

Comparison of ecological factors

The characteristics of ecological factors were listed in Table 3. The results indicated that the main ecological factors such as annual rainfall, evaporation, annual temperature, accumulated temperature and frost-free period in the area of Mongolian pine plantations were 496 mm, 1700 mm, 5.9°C, 3067-3148°C, 160 days, respectively, which were 118 mm, 526 mm, 6.3-9.6°C, 1067-148°C, 70 days higher than those in the area of natural Mongolian pine forest, respectively. While, the mean height above sea level (ASL), moisture index, latitude and species richness of vegetation in the area of Mongolian pine plantation were less than those in the area of natural Mongolian pine forest. Particularly, the difference of ASL was more than 600 m between the two origins of forest areas. There were no significant differences in nutrient, construction and depth of soil between the two forest areas (Table 3).

Diameter class distribution

Three distribution functions were used to check the diameter class distribution of the sample plots in the two origins of Mongolian pine stands. Comparisons of the distributions obtained from moment-based parameters and the goodness-of-fit results were shown in Table 4. In the sample plots of artificial forest, the Weibull distribution function was much better to fit the diameter class distribution, 34 for Weibull distribution (91.9%), 29 for normal distribution (78.4%) and 23 for Beta distribution (62.2%). The Weibull distribution had the least sum of Chi-square values; Beta distribution had the largest sum of Chi-square values. The diameter class distribution curves in artificial stands were mound shaped and reversed-J shaped, for $c < 1$ in equation (3) by 46% of the sample plots, and $1.82 \leq c \leq 2.75$ by 54% of the sample plots (Fig. 1A, 1B). However, in the sample plots of natural stand, the Normal distribution had the greatest number, 9 sample plots for normal distribution (81.8%), 6 for Weibull distribution (54.5%) and 4 for Beta distribution (36.4%). The Normal distribution had the least Chi-square values, and Beta distribution had the largest Chi-square values. The distribution curves of diameter class in natural Mongolian pine stands were mound shaped in symmetry (Fig. 1C). Mongolian pine plantations in NHHI region showed the same tendency as Mongolian pine plantations in PKZL region; but this tendency was excluded from further analysis because of less sample plots.

The difference in diameter class distribution between the two origins of Mongolian pine stands may be mainly due to the disturbances such as thinning, caring (Table 3), and higher density (Table 1) in plantations. The Weibull and Normal distribution functions were proposed as diame-

ter-class distribution models in artificial and natural stands, respectively.

Table 3. Ecological factors and natural situation of Mongolian pine forests on sandy land with different origins, artificial and natural forests

Group	Location (longi- tude and latitude)	Precipitation /mm (Average in 10 years)	Evaporation /mm (Long term)	Annual mean temperature /°C	≥10°C Effective accumulated temperature/°C	Absolute minimum temperature Average in 10 years) /°C (
Honghuaerji, Hu- lunbeier sandy land	N47°35'-48°36' E118°58'-120°32'	378	1 174	-3.7	2 000	-45.0
Zhanggutai, Keerqin sandy land	N42°43'-43°20' E122°22'-123°22'	496	1 700	5.9	3 067-3 148	-30.4
Group	Annual daily hour /h (Long term)	Frost free period /d (Long term)	Above sea level /m	Average wind speed / m · s ⁻¹	Moisture index	Origin of sandy land
Honghuaerji, Hu- lunbeier sandy land	2 500-3 000	90	700-1 000	3.8	0.323	Alluvial, aeolian and lacustrine sand fixed sand dune
Zhanggutai, Keerqin sandy land	2 600-2 700	160	226.5	3.7-4.6	0.292	Alluvial sand dune, mobile, semi-mobile and fixed sand dune
Group	Sand soil type	Physical sand particle (In 50 cm)	Average depth of sand land / cm	Soil nutrient (In 50 cm)	Disturbance	
Honghuaerji, Hu- lunbeier sandy land	Pine sandy soil and soddy sandy soil	≥ 0.01 mm, 91.7%, <0.01 mm, 8.3%	0-90	Quick acting phosphate: 0.01-0.015%, quick acting nitro- gen: 0.02-0.03%	Grazing, Mushroom picking	
Zhanggutai, Keerqin sandy land	Mobile sandy soil and soddy sandy soil	≥ 0.01 mm, 94.0%, <0.01 mm, 6.0%	0-107	Quick acting phosphate: 0.01%, quick acting nitrogen: 0.02%	Human activities such as needle collection, thinning and caring	
Group	Vegetation	Reprehensive plants				
Honghuaerji, Hu- lunbeier sandy land	Da- vuri-Mongolian flora	<i>Filifolium sibiricum</i> , <i>Stipa baicalensis</i> , <i>Festuca ovina</i> , <i>Carex pediformis</i> , <i>Hemerocallis keiskei</i> , <i>Sanguisorba officinalis</i> , <i>Saposhnikovia davurica</i> , <i>Iris dichotoma</i> , <i>Pulsatilla turczaninovii</i> , <i>Bupleurum</i> sp., <i>Polygomatum humile</i> , <i>Potentilla fragarioides</i> , <i>Carex</i> spp., <i>Spirea</i> spp., <i>Lespedeza davurica</i>				
Zhanggutai, Keerqin sandy land	Huabei flora	<i>Agropyron cristatum</i> , <i>Arundinella hirta</i> , <i>Cleistogenes chinensis</i> , <i>Lespedeza davurica</i> , <i>L. hedysaroides</i> , <i>L. bicolor</i> , <i>Artemisia aurata</i> , <i>A.Capillaris</i> var. <i>simplex</i> , <i>A. sacrorum</i> , <i>A. frigida</i> , <i>Setaria viridis</i> , <i>Potentilla fragarioides</i>				

Table 4. Summary of mean and ranges of Chi-square statistics for the three distribution models

Group	Age /year	Skewness	Chi-square (0.05)	Chi-square in Normal distribution	Chi-square in Weibull distribution	Chi-square in Beita distribution
Plantation in PKZL n=37	20.9 (11- 39)	-0.097 (-0.642- 0.358)	9.063 (5.992-5.507)	6.216 (0.204-23.135) m=29	-2182.344 (-30860.7-19.1245) m=34	9.790 (1.0036-41.4451) m=23
Plantation in NHHI n=2	26.0 (26)	-0.058 (-0.146-0.029)	14.05 (12.592-15.507)	7.244 (6.026-8.461) m=2	6.888 (2.331-11.445) m=2	7.974 (4.503-11.445) m=2
Natural stand in NHHI n=11	37.91 (22-66.5)	0.251 (-0.999-2.042)	17.517 (9.488-24.996)	30.791 (1.898-172.751) m=9	45.345 (-332.711-714.349) m=6	80.685 (4.116-354.53) m=4

Note: n: the number of sample plots; m: the number of fitted distribution ($p < 0.05$).

PKZL: Ke'erqin sandy land, Zhanggutai of Liaoning Province; NHHI: Hulunbeier sandy land, Honghua'erji of Inner Mongolian Autonomous Region.

Growth processes of Mongolian pine trees

Chapman-Richards function was employed to fit total growth-age trajectories in both artificial and natural Mongolian pine stands by using stem analysis data (Equation 6). It

generally provided a good fit of the growth-age data. The coefficients of determination (R^2) averaged at 0.873, and ranged from 0.738 to 0.972 (Table 5). The models of diameter and height were also checked with the average values of diameter and height from sample plots. The re-

sults showed that there are no significant differences between the fitted data and the sampled data.

Fig. 2 shows the total growth of DBH-age, tree height-age and volume-age in the Mongolian pine artificial and natural forests. Means, standard deviations, covariance and coefficients of determination among the parameters of G_{ias} , ω_i and λ_i were listed in Table 5.

In simulation of diameter growth, the number of years is required to reach the age when the height = 1.3 m, therefore, the growth model parameters in DBH curves should have initial age t_0 . If equation (7) is the height growth, the initial age (t_0) can be obtained by replacing $G_h(t)=1.3$ m as showed in equation (8).

$$G_h = G_{has} [1 - \exp(-\omega_h t)]^{\lambda_h} \quad (7)$$

$$t_0 = (1 - \omega_h) \ln[1 - (1.3 / G_{has})^{1/\lambda_h}] \quad (8)$$

Substituting the parameters from the results summarized in Table 5 to equation (8), the initial age of DBH (t_0) was determined as: $t_0=6.60$ in Mongolian pine plantation, and $t_0=8.54$ in Mongolian pine natural stand.

The Chapman-Richards growth function is based on relative growth rate, thus the first derivative of $G_i(t)$, representing as $G_i(t)/dt$, is of a size characteristic of growth function $G_i(t)$. From the derivative with respect to $G_i(t)$, the following equations of relative growth rate ($S_i(t)$) and average growth rate ($S_{imean}(t)$) can be obtained.

The relative growth rate (current annual increment)

$$S_i(t) = G_i(t) / dt = G_{ias} \omega_i \lambda_i \exp(-\omega_i t) [1 - \exp(-\omega_i t)]^{\lambda_i - 1} \quad (9)$$

and the average growth rate (mean annual increment)

$$S_{imean} = G_i(t) / t = (1/t) G_{ias} [1 - \exp(-\omega_i t)]^{\lambda_i} \quad (10)$$

Both the relative growth rates (equation 9) and average growth rates (equation 10) of diameter, height and volume can be obtained based on the fitted values of the parameters G_{ias} , ω_i and λ_i (Fig. 3). The maximum of the relative growth rate, which is the inflection of the growth rate (S_{imax}), can be determined of equation (9) as showed in equation (11).

$$S_{imax} = G_{ias} \omega_i (1 - 1/\lambda_i)^{\lambda_i - 1} \quad (11)$$

The age when S_{imax} occurs (A_{vimax}) can be obtained as equation (12).

$$A_{vimax} = -(1/\omega_i) \ln(1/\lambda_i) \quad (12)$$

If $t_0 \neq 0$, equation (12) becomes

$$A_{vimax} = \omega_i t_0 - (1/\omega_i) \ln(1/\lambda_i) \quad (13)$$

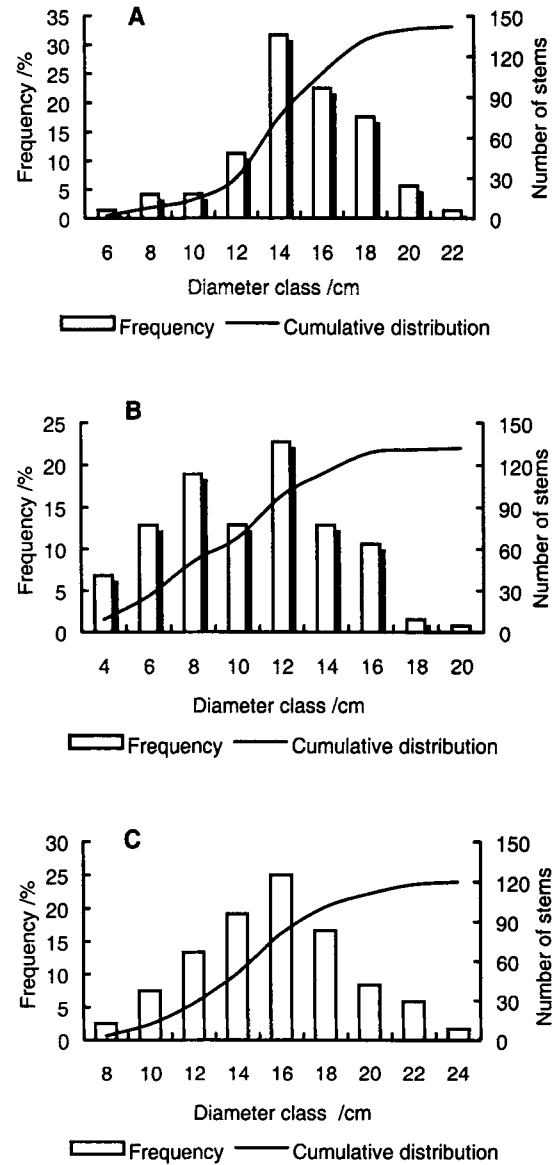


Fig. 1 Diameter class distributions.

A: Weibull distribution function with $c < 1$ in artificial stands of Mongolian pine, B: Weibull distribution function with $1.82 \leq c \leq 2.75$ in artificial stands of Mongolian pine, C: Standard Normal distribution function in natural stands of Mongolian pine.

In the same way, the maximum and the corresponding age of average growth rate can also be obtained from the derivative of equation (10).

The incremental acceleration ($A_i(t)$) in growth rate can also reflect the growth situations, especially for volume growth.

$$A_i(t) = G^2(t) / dt^2 = G_{ias} \omega_i^2 \lambda_i \exp(-\omega_i t) [\lambda_i \exp(-\omega_i t) - 1] [1 - \exp(-\omega_i t)]^{\lambda_i - 2} \quad (14)$$

Solving equations (9)-(14), we determine the characteristic values of growth in diameter, height and volume for the

trees in the two origins of Mongolian pine forest, and find that the values between the trees in the two origins have the apparent differences (Table 6, Fig. 3, and Fig. 4).

less than that of natural stand trees afterwards. The average growth rate achieved its peak at year 24 with $0.504 \text{ cm} \cdot \text{a}^{-1}$, but it decreased very quickly and was less than that of natural stand trees from 53 years (Fig. 2A and 3A).

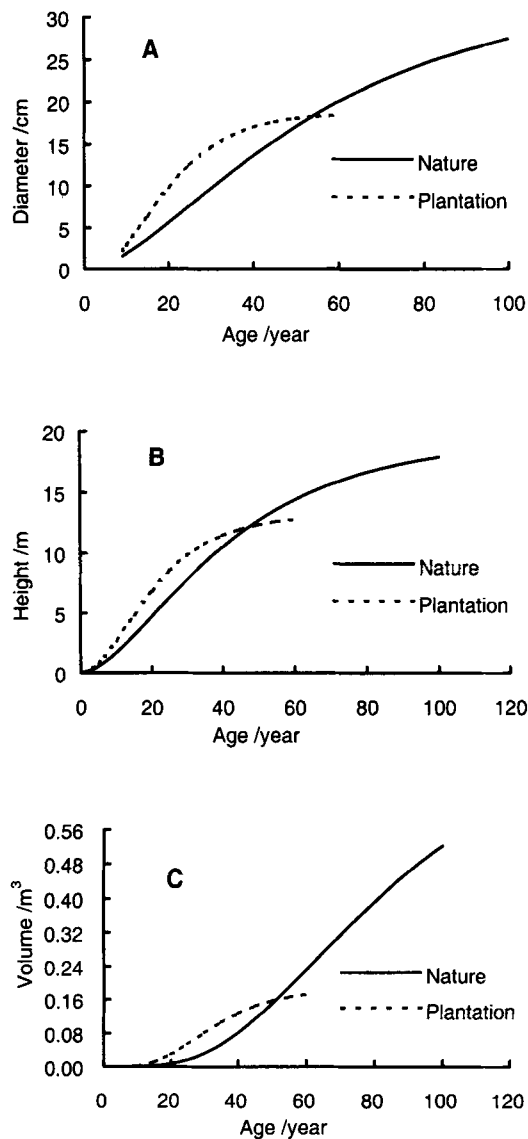


Fig. 2 Fitted total growth curves for both artificial stands and natural stands of Mongolian pine.

A: diameter growth, B: height growth, C: volume growth.

Diameter growth

Growth of DBH for natural stand trees started at year 8.5 (equation 8), the relative growth rate (equation 9) increased with increment of age till 25 years and reached its maximum of $0.412 \text{ cm} \cdot \text{a}^{-1}$. The average growth rate (equation 10) achieved its peak at year 46 with $0.343 \text{ cm} \cdot \text{a}^{-1}$. The artificial stand trees followed a similar trend to the natural stand in DBH growth, which started at year 6.6 with a higher growth rate of $0.448 \text{ cm} \cdot \text{a}^{-1}$; and reached its maximum of $0.723 \text{ cm} \cdot \text{a}^{-1}$ at year 14. However, it decreased abruptly with the increasing of age, dropped to a low value of $0.419 \text{ cm} \cdot \text{a}^{-1}$ at year 27. After the age of 27 years, it was

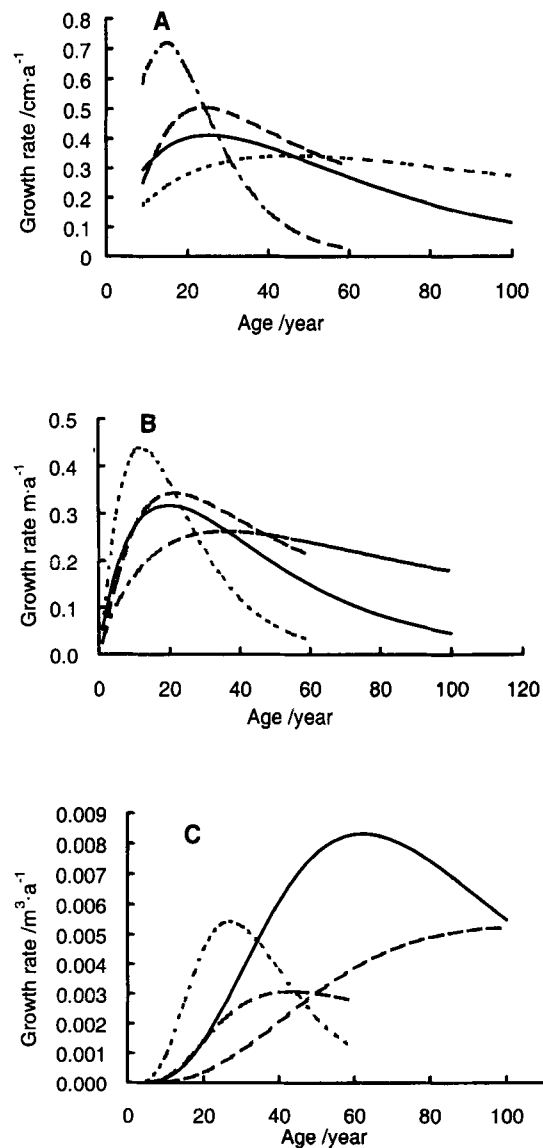


Fig. 3 Relative growth rate and average growth rate.

A: diameter, B: height, C: volume.

— Relative growth rates for natural stand
 --- Relative growth rates for artificial stand
 ... Average growth rates for natural stand
 -.- Average growth rates for artificial stand

Height growth

In general, the rate of height growth increases with increasing of age and decreases after a certain age (Fabbio *et al.* 1994). The relative growth rates achieved their peaks at year 21 and 12 for natural stand and artificial stand trees, respectively. The intersection between the curves of relative growth rate and average growth rate is an estimate of the point after which the relative growth rate is less than that of average growth rate. The two curves of relative and

average growth rates intersected at year 21 and 37 for artificial and natural stands, respectively (Fig. 3B).

Table 5. Summary of parameter values for the accepted growth-age trajectories in the two different origins of Mongolian pine forests on sandy land (Refer to equation 6)

	Observation	G_{las}	λ_i	ω_i	Coefficients of determination (R^2)	Standard deviation of $[1-\exp(-\omega_i t)]$ (SD)	Covariance
Artificial stands							
Diameter	95	18.75	3.6070	0.0900	0.816	1.7895	11.544
Height	117	13.18	2.3425	0.0705	0.972	4.2116	41.549
Volume	117	0.1900	6.9199	0.0720	0.949	4.0798	115.177
Nature stands							
Diameter	151	32.16	1.8835	0.0250	0.738	4.4127	36.4744
Height	173	19.34	1.8879	0.0320	0.882	6.3283	75.6062
Volume	173	0.7608	5.3510	0.0269	0.882	6.7251	242.1130

Table 6. Statistics of characteristics for Chapman-Richards growth models

	Diameter				Height				Volume			
	ACGR	CGR	AAGR	AGR	ACGR	CGR	AAGR	AGR	ACGR	CGR	AAGR	AGR
Artificial stand	14	0.7236	24	0.5040	12	0.4300	21	0.3428	27	0.0054	43	0.0031
Natural stand	25	0.4116	46	0.3423	20	0.3170	37	0.2625	62	0.0077	102	0.0052

Note: ACGR: Age at maximum of current growth rate /a; CGR: Current growth rate / $\text{cm} \cdot \text{a}^{-1}$; AAGR: Age at the maximum of average growth rate /a; AGR: Average growth rate / $\text{cm} \cdot \text{a}^{-1}$.

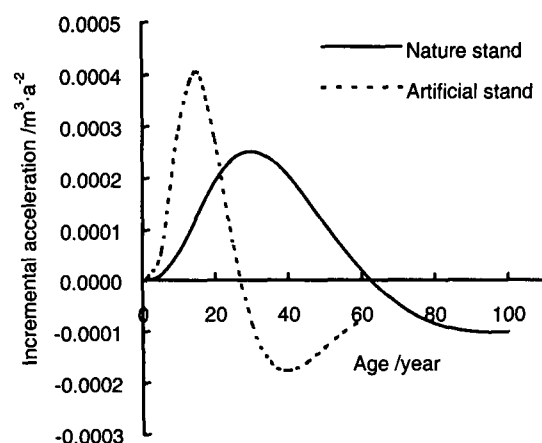


Fig. 4 Incremental accelerations of volume for artificial stands and natural stands of Mongolian pine.

Volume growth

Volume growth is considered directly proportional to diameter and height growth (Fabbio *et al.* 1994). The age of maximum of relative growth rate, quantitative maturity age and the age of minimum of incremental acceleration rate in both origin stands were shown in Fig. 3C and Fig. 4. The maxima of relative growth rates were $0.0054 \text{ m}^3 \cdot \text{a}^{-1}$ at year 27 and $0.0077 \text{ m}^3 \cdot \text{a}^{-1}$ at year 62 for artificial and natural stand, respectively. The quantitative maturity ages were 43 years and 102 years for artificial and natural stands, respectively. The age at the minimum of the incremental ac-

celeration rate ($A_v(t)$), defined in equation (14) is an estimate of volume growth tendency from which the volume growth becomes less and less. The ages and the minimum values of incremental acceleration occurred at year 90 with $-0.0001 \text{ m}^3 \cdot \text{a}^{-2}$ and at year 39 with $-0.00018 \text{ m}^3 \cdot \text{a}^{-2}$ for Mongolian pine natural and artificial stands, respectively.

The differences of growth between Mongolian pine trees from the two origins showed that the ages of maximum of relative growth rate and average growth rate for artificial stand trees of DBH, height, and volume were 11, 22 years, 8, 15 years and 35, 59 years earlier than those of natural stand trees, respectively. These results meant that the artificial stand trees developed faster than those of natural stand trees on sandy land before certain ages. It may be concluded that the life of artificial stand trees of Mongolian pine was about 60 years shorter than that of natural stand trees because the difference of quantitative maturity age between the two origins was 59 years. These differences between the two origins of Mongolian pine trees may be due to the following variations: the drastic variations including latitude of $4^{\circ}52' - 5^{\circ}16'$, annual temperature of 9.6°C , frost free period of 70 days, ASL of 600 m, and moisture index of 0.031 may contribute to the differences of growth for Mongolian pine trees from different origins (Table 3). The higher stem density of Mongolian pine plantation may also produce the growth differences because of water competition. According to the research result by Zeng *et al.* (1996b), the suitable density of Mongolian pine plantation on sandy land is $1500 \text{ stems} \cdot \text{hm}^{-2}$ at year 15, however, the average density of Mongolian pine plantation was more than $1600 \text{ stems} \cdot \text{hm}^{-2}$ at year 21. Additionally, disturbances

in plantations such as needle collection, thinning and caring and so on may also cause the differences.

Conclusions

The growth of Mongolian pine between the two origins were very different, i.e., the total growth of DBH, height and volume in artificial stands developed earlier than those in natural stands, but the duration of growth in artificial stands was much less than that of natural stands. The results of quantitative maturity ages suggested that the life of Mongolian pine artificial stands trees was about 60 years less than that of natural stand trees. The differences may mainly be due to the drastic variation in main ecological conditions such as latitude, ASL, temperature and moisture index, higher stem density and human beings' activities in plantations. Weibull and Normal distribution functions were proposed as diameter-class distribution models for artificial and natural stands, respectively.

Acknowledgement

We would like to acknowledge Dr. Yuanrun Zheng, Prof. Shuren Jiao, Dr. Xiangyun Wu and Ms. Heming Lin, who attended part of the field investigation and performed soil analysis. We are also grateful to Institute of sand fixation and silviculture, Liaoning province, Institute of Protective Forests, Heilongjiang Province, Forestry Bureau of Honghuaerji, Inner Mongolian Autonomous region, and Forestry Factory of Fujia, Liaoning Province in China for providing the related information.

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